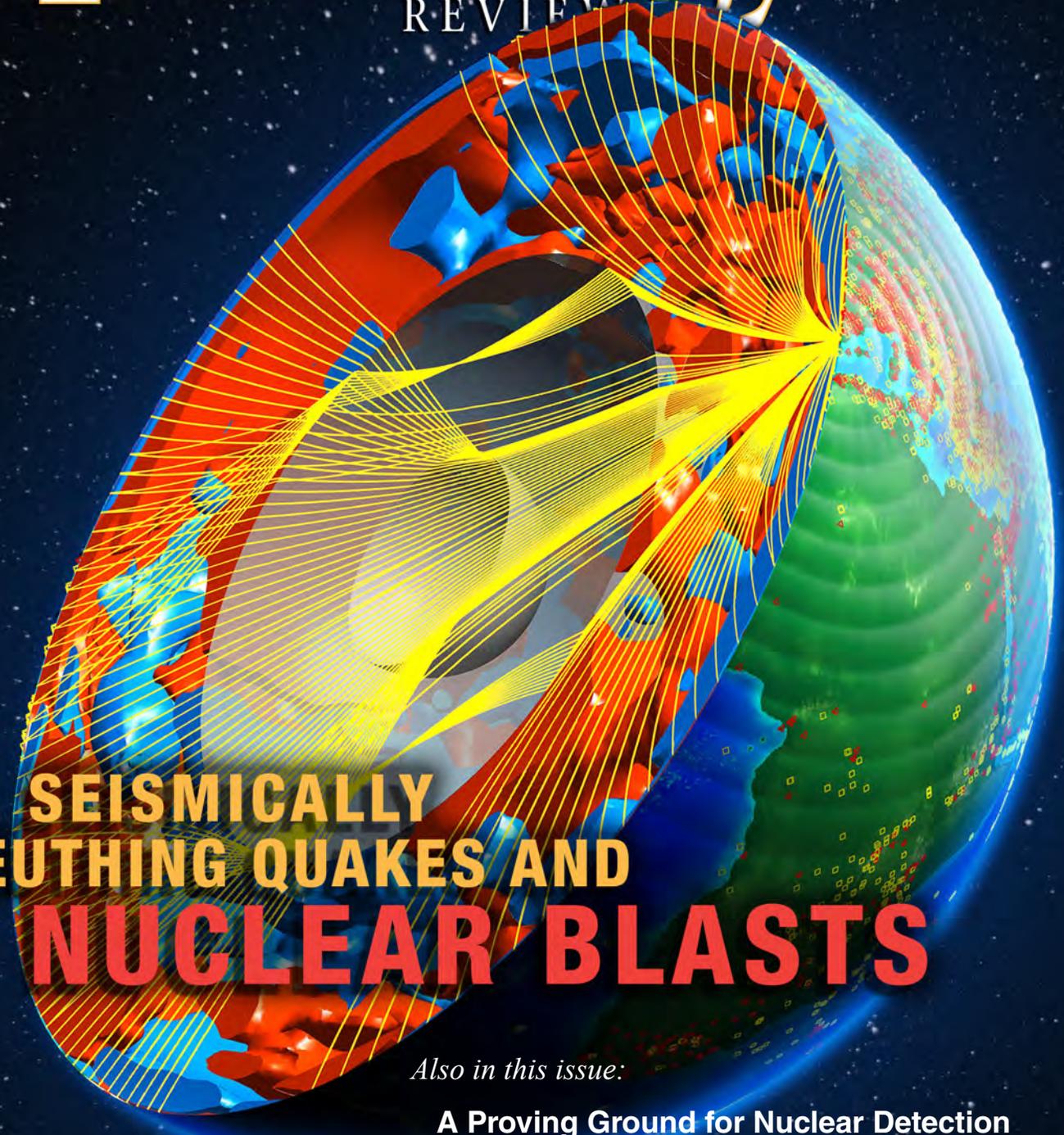


Science & Technology

REVIEW



**SEISMICALLY
SLEUTHING QUAKES AND
NUCLEAR BLASTS**

Also in this issue:

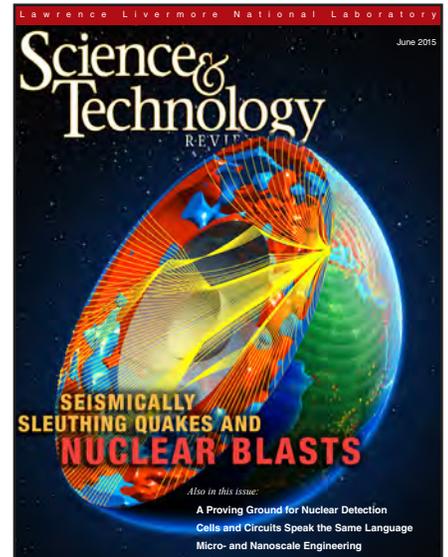
A Proving Ground for Nuclear Detection

Cells and Circuits Speak the Same Language

Micro- and Nanoscale Engineering

About the Cover

Lawrence Livermore scientists have long been leaders in seismic research to support monitoring under international treaties concerning nuclear explosive testing. As the article beginning on p. 4 describes, one of the Laboratory's most significant accomplishments is a revolutionary seismic monitoring technology called the Regional Seismic Travel Time (RSTT) model. RSTT improves the accuracy of locating seismic events by incorporating regional seismic data—that is, data from monitoring stations closest to the event—and by using a sophisticated three-dimensional (3D) model of Earth's crust and upper mantle. An improved version called LLNL-Global 3D (G3D) extends velocity profiles from the crust and upper mantle used in RSTT. On the cover is a cutaway of Earth from an actual LLNL-G3D simulation of seismic waves (yellow lines) propagating through Earth's interior. Added to the simulation image are effects representing surface waves from the hypothetical seismic event.



Cover design: Amy E. Henke; Rendering: Ryan Chen

About S&TR

At Lawrence Livermore National Laboratory, we focus on science and technology research to ensure our nation's security. We also apply that expertise to solve other important national problems in energy, bioscience, and the environment. *Science & Technology Review* is published eight times a year to communicate, to a broad audience, the Laboratory's scientific and technological accomplishments in fulfilling its primary missions. The publication's goal is to help readers understand these accomplishments and appreciate their value to the individual citizen, the nation, and the world.

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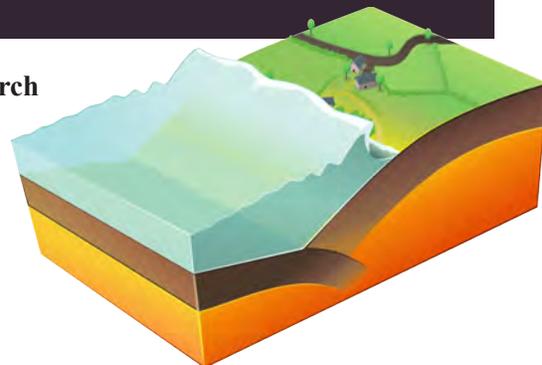
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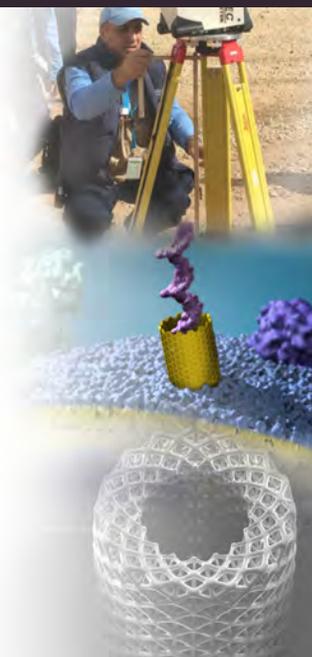
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In Memoriam: Richard Freeman “Dick” Post

Richard Post, a lifelong scientist who passed away on April 7, 2015, at age 96, joined Lawrence Livermore National Laboratory within weeks of its founding in 1952 and worked here for 63 years. Even after initially retiring in 1991, he continued his research, driven by a keen awareness of humankind’s need for clean, efficient energy.

Post pioneered the fusion-energy approach of using magnetic mirrors to confine the fusion reaction. His groundbreaking work on flywheels for energy storage—including seminal papers authored in the 1970s—established his reputation as the father of the modern flywheel for energy storage, envisioning flywheels made of lightweight composites and spinning at supersonic speeds in a vacuum chamber, magnetically suspended in a frictionless state.

Post’s many awards and honors include being among the first recipients of the American Physical Society’s James Clerk Maxwell Prize in 1978 and winning an R&D 100 Award in 2004 for his design of a magnetic levitation train. His name is on 34 patents—nine of which he obtained after the age of 90. Laboratory Director Bill Goldstein commented, “Dick Post is a legend. His unique contributions to the Lab have spanned its entire existence and enriched our place in history. It was an honor to have known him.”

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Mercury’s Dark Surface Explained

In a study published online in the March 30, 2015, edition of *Nature Geoscience*, researchers reported that carbon, delivered by comets or comet dust, is the “stealth” agent darkening Mercury’s surface—a mystery that had long puzzled planetary scientists

in light of the planet’s low level of iron, an important darkening material in airless bodies such as the moon and asteroids.

Numerical calculations to assess the impact delivery of carbon on Mercury found that micrometeorites, which are mostly derived from carbon-enriched comets, would deliver enough carbon to affect observations of Mercury’s surface. These micrometeorites’ relatively low-impact velocities allow most material to be retained by the planet, resulting in surface carbon abundances of three to six percent, thereby darkening the planet.

“Understanding the role of micrometeorites in delivering dark material to Mercury provides new ways of interpreting observations of the planet,” says lead author Megan Bruck Syal, a postdoctoral researcher at Lawrence Livermore. “In addition, we are now working to understand how micrometeorites may have delivered other materials of interest to Mercury, including water.”

Hypervelocity impact experiments at NASA’s Ames Vertical Gun Range also tested whether carbon could be effectively entrained within glassy, impact-generated melt products, resulting in darker spectral signatures. The results were consistent with remote sensing observations of Mercury by the MESSENGER mission, further suggesting an important role for carbon on Mercury’s surface.

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Impact of Target “Tents” for National Ignition Facility

Ultrathin mounting membranes for inertial confinement fusion targets used at the National Ignition Facility (NIF) consist of two plastic membranes holding the target capsule at the center of the hohlraum. The membranes, called tents, were originally estimated to have an acceptable effect on implosion. However, results from a systematic study published in the February 4, 2015, edition of *Physics of Plasma* showed that in low-adiabat implosions, the tent seeds a perturbation that induces Rayleigh–Taylor hydrodynamic instabilities, affecting symmetry and thereby reducing the implosion’s yield.

The researchers used x-ray area-backlit imaging to assess in-flight, low-mode, two-dimensional asymmetries of the shell. The time-resolved images revealed features that can be related to the liftoff position of the tent membranes.

The experimental data suggest that in the implosions, the tents seed hydrodynamic instabilities at the capsule surface from the beginning, which grow throughout the implosion until they eventually come close to perforating the capsule. On the other hand, in higher adiabat shots the tent’s impact is significantly less because of lower overall hydrodynamic instability in the implosion.

“This work,” the researchers say, “shows that it is important to use mounting membranes that are as thin as possible. We need to find mitigation strategies, for example, in the form of the laser pulse shapes for less instability growth or in alternative mounting strategies.”

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A Proud History of Seismic Research

ALTHOUGH most often associated with detecting earthquakes, seismic technology is also the primary method to detect and locate underground nuclear explosions. Lawrence Livermore's seismic research program began in the 1960s, when our weapons program needed a method to promptly determine the yield of underground nuclear explosive tests conducted at the Nevada Test Site. In response, the Laboratory's first group of earth scientists set up four seismic stations to form a network around the test site that provided data immediately after a detonation.

Seismic research efforts received a boost from Project Plowshare, created in 1957 by the U.S. Atomic Energy Commission to explore the use of nuclear explosives for peaceful purposes. Some of the Plowshare tests were conducted to determine the characteristics of the resulting underground seismic signals, thereby enhancing our knowledge of how seismic waves travel through different geologic strata.

In 1963 the Limited Test Ban Treaty banned nuclear explosions in the atmosphere, outer space, and underwater. With nuclear explosions confined to below ground, Livermore seismologists faced significant challenges in distinguishing nuclear explosions from earthquakes and mining explosions. The ability to do so is important for monitoring underground nuclear explosions worldwide.

Within a few years seismologists provided an important new technology: digital seismographs running continuously at the test site and acquiring data from infrequent nuclear explosions, as well as from earthquakes large and small. In the early 1980s, the Department of Energy deployed the Regional Seismic Test Network, composed of five continuously recording seismic stations around the United States and Canada. Livermore scientists helped to analyze the reams of data these sensitive stations captured.

By the early 1990s, the fall of the Soviet Union and the end of the Cold War gave renewed impetus for a Comprehensive Nuclear-Test-Ban Treaty (CTBT). The U.S. ceased nuclear explosive testing in 1992, and the CTBT was signed by President Clinton and other heads of state and government in 1996.

The Laboratory has played a significant role in supporting the CTBT's international system of automated seismic monitoring stations. The stations transmit data via satellite to the International Data Center in Vienna, Austria, which in turn distributes the data to national data centers around the world for analysis.

Livermore supports the U.S. National Data Center (NDC) at Patrick Air Force Base in Florida, which is responsible for U.S. nuclear explosion monitoring as part of its international treaty monitoring mission. Our diplomats and scientists recognize that the value of nuclear treaties rests, in large part, on the technical capabilities available for monitoring compliance.

Several years ago, the U.S. NDC requested a technique to integrate regional-distance seismic data with its conventional long-range data. In response, Livermore seismologist Stephen Myers led a research effort that included scientists from Los Alamos and Sandia national laboratories. As the article beginning on p. 4 describes, the resulting technology—the Regional Seismic Travel Time (RSTT) model—improves the accuracy of locating seismic events by using a three-dimensional (3D) model of Earth's crust and upper mantle to accurately incorporate regional seismic data for enhanced detection. Small-yield events are detected quickly and with an accuracy once achieved only with large, globally recorded events. The program has already been adopted by many nations. In addition, RSTT permits seismologists to better locate and characterize local earthquakes, their primary task.

Livermore seismic researchers are currently pursuing even more-accurate 3D models and developing new “big data” applications. Currently, each seismic event is analyzed on its own, independent of hundreds of previous seismic events in the same region. We are looking for ways to exploit the enormous data set we have accumulated over more than 60 years. Combined with 3D Earth models, we will then be able to create high-fidelity “synthetic” waveforms that any seismic station is likely to see. With these and other forthcoming advancements, a rogue nation or terrorist group attempting to silently set off a small clandestine nuclear explosion is likely to create a thunderous seismic disturbance that the entire world will “hear.”

■ Jay Zucca is principal deputy to the principal associate director for Global Security.

SEISMIC RESEARCH MAKING WAVES

Livermore scientists support international treaties on nuclear testing, understanding of Earth's evolution, and preparations for major earthquakes.

SEISMIC waves from earthquakes, volcanoes, and man-made explosions can propagate through Earth's interior for thousands of kilometers. Tens to hundreds of events per day are routinely detected by hundreds of seismometers arrayed around the world. These seismic signals are carefully scrutinized to determine whether any one of the events was an underground nuclear explosion, which would violate the Comprehensive Nuclear-Test-Ban Treaty (CTBT). CTBT is a key global tool for preventing the proliferation of nuclear weapons.

Lawrence Livermore scientists have long been leaders in seismic research to support such international nuclear explosive testing treaties, which date back more than a half-century. Treaty verification research includes developing complex models of geologic structure that are used to understand how seismic waves are distorted while propagating

from source to receiver. The models are also used in basic earth science research to deduce the past and future evolution of our planet, including the formation and movement of giant tectonic plates. That effort has identified new features deep inside Earth, including an ancient, buried tectonic plate beneath the Indian Ocean.

Laboratory scientists and engineers are also conducting chemical explosives tests to refine models of seismic wave generation and are using Livermore's advanced "big data" technologies—that is, data-intensive computational science—to glean new insights from the vast amounts of seismic data accumulated over six decades of nuclear monitoring. Finally, researchers are using supercomputer simulations to better understand ground motions from earthquakes as a means to help California prepare for major temblors expected to strike the state in the future.

Sweeping the Globe

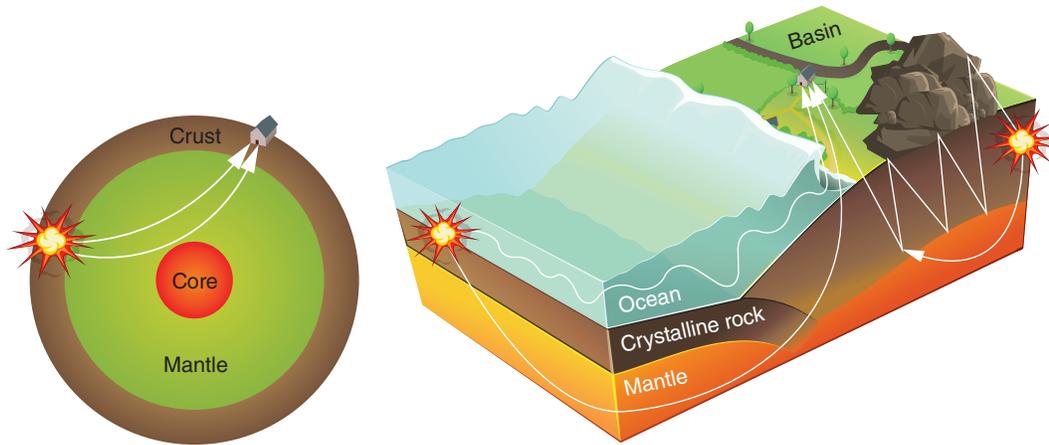
One of the Laboratory's most significant accomplishments in the seismic sciences is a revolutionary seismic monitoring technology called the Regional Seismic Travel Time (RSTT) model and computing code. Developed with colleagues from Los Alamos and Sandia national laboratories, RSTT improves the accuracy of locating seismic events by incorporating a three-dimensional (3D) model of Earth's crust and upper mantle and regional data—which are needed for enhanced detection—into existing monitoring systems established in the 1960s through the present. RSTT also offers blazing speed: In less than 1 millisecond, the system calculates the seismic-wave travel times that are used to locate seismic events through triangulation. Since 2010, RSTT has been provided to all CTBT member states so their monitoring organizations can all consistently determine the location of a seismic event.

The model earned Livermore seismologist Stephen Myers the Department of Energy’s prestigious E. O. Lawrence Award in 2014. A researcher in Livermore’s Global Security directorate, Myers was recognized for leading RSTT development as part of Livermore’s enduring nuclear nonproliferation efforts.

For more than three decades, several nations conducted aboveground nuclear tests, but in 1963 the Limited Test Ban Treaty—signed and ratified by the United States, the United Kingdom, and the Soviet Union—banned nuclear explosions in air, oceans, and space. The last aboveground nuclear explosive test was conducted in 1980, by China. The Threshold Test Ban Treaty, which became effective in 1990, limited underground nuclear weapons explosions by the U.S. and Soviet Union to 150 kilotons.

Signed by President Clinton and other heads of state in 1996, CTBT banned all nuclear explosions and provided the framework for international monitoring to detect underground nuclear explosions. This monitoring network uses four technologies: seismic, hydroacoustic, infrasound, and radionuclide. Of these, seismic sensors are the most sensitive to signals from explosions underground, which is the most likely environment for future nuclear explosions, announced or not.

The Preparatory Commission for the CTBT Organization, headquartered in



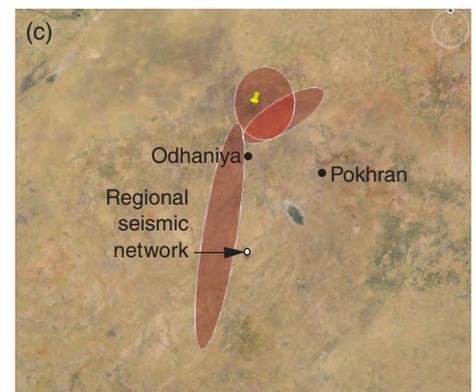
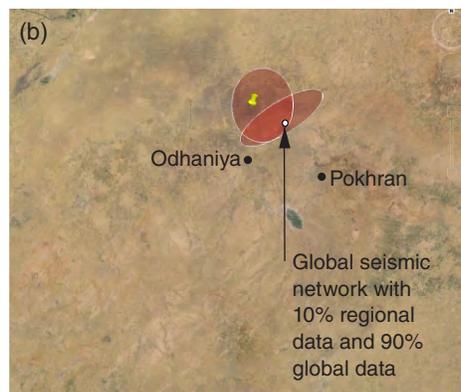
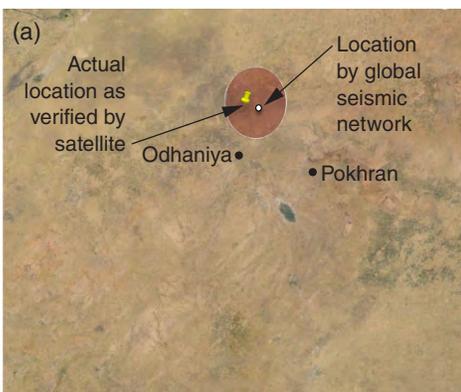
(left) For decades scientists successfully employed a simple, one-dimensional (1D), radially symmetric model of Earth to monitor the large nuclear tests that were allowed under the Limited Test Ban Treaty. These strong signals propagated mainly through Earth’s lower mantle, where velocity perturbations are minimal. (right) However, signals from a small test propagate predominantly in Earth’s upper mantle and crust, following paths that vary greatly depending on local geology—resulting in large errors in travel-time prediction.

Vienna, Austria, is making preparations to implement CTBT. The organization’s International Data Center receives data from monitoring stations and forwards both raw and analyzed data to member states. The U.S. National Data Center (NDC) at Patrick Air Force Base in Florida is responsible for U.S. monitoring under the treaty. The National Nuclear Security Administration (NNSA) laboratories provide data-analysis algorithms and technology needed for the U.S. NDC to lower monitoring thresholds and improve monitoring performance.

Several nations, including India, Pakistan, and North Korea, have not

signed CTBT, and all three have conducted underground tests since CTBT was signed. The most recent announced underground nuclear test was conducted in 2013 by North Korea and generated a magnitude-5.1 seismic event. As with North Korea’s two other underground explosions, in 2006 and 2009, member states received information about the location, magnitude, time, and depth of the explosions within two hours, before the test was even announced by North Korea.

Myers explains that as underground tests become smaller, as evidenced with the North Korean explosions, the monitoring task grows increasingly difficult. He says,



“As we entered the CTBT era, we saw the need to focus on smaller events, but these are not reliably detected at distances typified by established global monitoring networks [a distance of approximately 3,000 to 10,000 kilometers, also known as the teleseismic range].” Very small seismic events may only be detectable using seismic stations close to the test location.

Seismic Waves Tell the Tale

Seismic waves reflect and refract from geologically distinct layers: the crust, the upper mantle, the lower mantle, and the core. The speed of seismic waves depends on the elastic properties and density of the material through which they travel. Cold, stiff rocks allow seismic waves to travel quickly, whereas soft, molten rocks slow them down. The two types of seismic waves most useful for locating nuclear explosions are P-waves and S-waves. P-waves are faster than S-waves and so arrive first, followed by S-waves. The layered structure of Earth also results in several paths of propagation, so a seismogram consists of several P-wave and S-wave arrivals. To use these waves to pinpoint an event’s location, scientists must understand details of Earth’s structure and the physics of how that structure affects wave propagation.

For decades scientists successfully employed a simple one-dimensional (1D), radially symmetric model of Earth

to monitor the large nuclear explosions that were allowed under the Limited Test Ban Treaty. These strong signals propagate to teleseismic distances mainly through Earth’s lower mantle, where velocity perturbations are minimal. “These explosions were observed all over the world,” notes Myers. “The P- and S-waves were separated nicely in time and gave us clear, uncomplicated signals.” The 1D model predicts long-range P-wave travel times with an error of less than 0.3 percent.

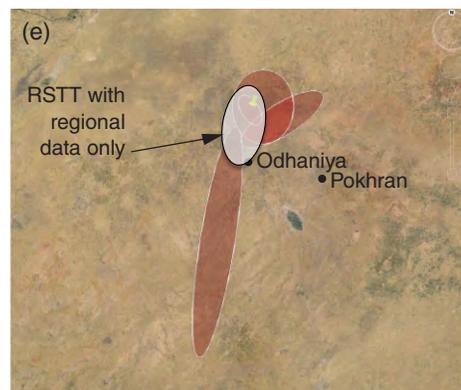
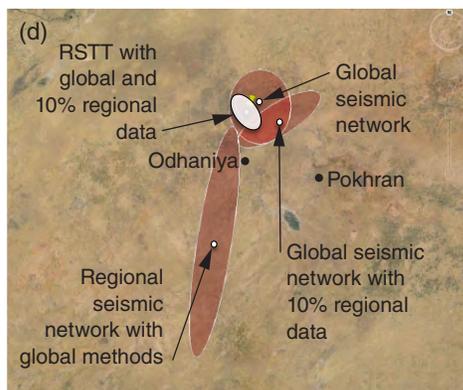
However, detectable signals from a small explosion propagate in Earth’s upper mantle and crust and involve regional distances—less than 2,000 kilometers—between event and sensor, with the error in travel time prediction increasing to as high as 10 percent. In other words, incorporating regional data into a global monitoring system could significantly increase error in event location. Furthermore, using regional data alone could result in a predicted location being off by many tens of kilometers. Nevertheless, the CTBT monitoring system cannot afford to ignore regional data because the amplitude of the signal from a very small event could dip below the background noise level recorded by a seismometer at teleseismic distances.

Concerned with the large errors inherent in predictions based on regional signals and a 1D model, the U.S. NDC tasked the NNSA laboratory team led by

Myers to develop a new technology that would enable incorporation of regional data into the monitoring system without increasing event location error. “Our goal,” says Myers, “was to confidently monitor at lower thresholds while maintaining location accuracy.” Making the task even more challenging, the U.S. NDC stipulated that the new model must be computationally efficient and “lightning fast” on a single-processor computer.

A Breakthrough in Three Dimensions

In 2006 Myers formed a scientific team of experts in signal propagation, signal analysis, and computations. By 2010, the team had developed a model that accounts for crust and upper-mantle variations in seismic velocity by dividing Earth’s surface into approximately 41,000 nodes that form the vertices of triangular tiles. Node spacing is approximately 1 degree of arc (about 111 kilometers), and a vertical profile of seismic velocity at each node is interpolated to render a 3D model of Earth’s crust and upper mantle. This 3D grid of seismic wave velocities depicts geologic structure, including variations in depth and the abrupt increase in wave velocity that occurs at the boundary between the crust and mantle, called the Moho discontinuity. The model is used to compute the arrival times of the waves that refract below the Moho discontinuity, as well as waves that are trapped in the crust.

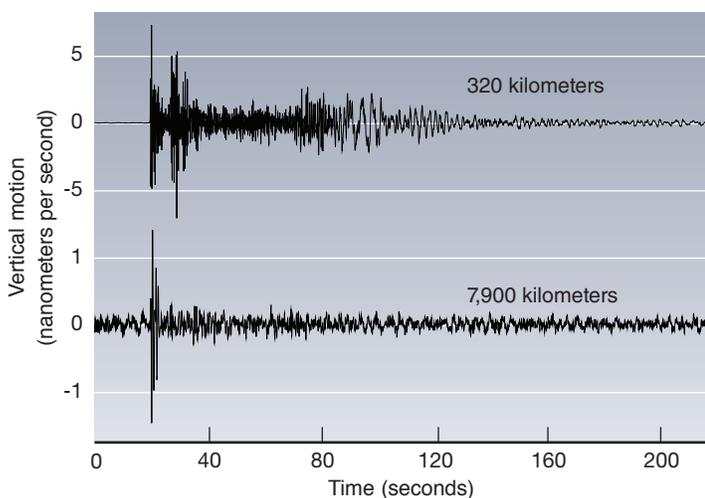


(a) Using a simple 1D model, the global network nearly pinpointed an underground nuclear explosion on May 11, 1998. The brown circle denotes a 95 percent probability region. (b) Including 10 percent regional data—potentially important because of proximity—with the model results in misidentification of the epicenter. (c) Using only regional data results in even greater error. (d) The Regional Seismic Travel Time (RSTT) model with global and regional data significantly (white area) improves the accuracy of event location. (e) Using RSTT with regional data alone (white area) includes the event location in its 95 percent probability area.

“RSTT represents the first time that a 3D model of Earth was specifically designed for monitoring,” Myers says. As a result, it reduces regional travel time error to the level of teleseismic error, thus allowing smaller events to be confidently located in monitoring systems. “It took the incorporation of regional data into the global monitoring system to lower monitoring thresholds to the point where people were more comfortable with seismic event location under the CTBT,” he says.

An important advantage of RSTT is that it narrows down the search area for an event by approximately a factor of 10 compared to the standard 1D global model. CTBT calls for an international on-site inspection if a dispute arises over whether

The Comprehensive Nuclear-Test-Ban Treaty monitoring system cannot afford to ignore regional data because the amplitude of the signal from a very small event could dip below the background noise level recorded by a seismometer at teleseismic distances (between 3,000 and 10,000 kilometers). Two seismograms (with different scales of vertical motion in nanometers) from a 2013 announced nuclear explosive test by North Korea show (top) data from a regional (about 320 kilometers from the source) seismic station and (bottom) from a teleseismic (about 7,900 kilometers away) station.



a treaty-violating underground nuclear explosion has occurred. Such an inspection is limited to 1,000 square kilometers, equivalent to a circle with radius of about 18 kilometers. (See article beginning on p. 12.) Clearly, the more accurate the location estimation, the smaller the inspection area will be, and the easier job the inspectors will have.

Event Type: Equally Important

Scientists determining the location of a seismic event must also distinguish an explosion from a host of possible nonnuclear events, such as conventional weapon explosions, mine explosions, earthquakes, and volcanic activity. “Travel times are to location as amplitudes are to identification of events,” says Myers. Typically, scientists examine the ratio of P-wave and S-wave amplitudes as an indicator of the seismic event type. An explosion radiates seismic waves outward from a point and typically generates stronger P-waves than S-waves, whereas earthquakes are lateral slips on fault planes that predominantly generate S-waves. However, some earthquakes may appear as explosions because S-waves can greatly decrease in amplitude when propagating through underground regions with strongly attenuating rocks.

“The underground nuclear tests conducted by North Korea challenged traditional methods for determining event type,” says Myers. Fortunately, incorporating regional data reduces that ambiguity. “Regional data helped to unambiguously determine that the North Korean events were indeed nuclear explosions.”

In light of the demonstrated success of RSTT in 2010, the

U.S. NDC recommended to the U.S. State Department that RSTT be shared with other nations. Four international workshops have been held to date to educate scientists from 66 nations on its use. “With everyone using RSTT we have a consistent framework, so we get consistent answers about the location and nature of an event,” explains Myers. Widespread use of the technology has also led to significant improvements in the model by incorporating regional data that were previously the domain of individual countries. The RSTT program runs on a laptop computer, a feature important to many international users. Myers adds that most national seismic organizations are focused on monitoring local earthquakes, and RSTT is also directly applicable to that purpose.

A Code That Goes Deep

The RSTT method is fast, reliable, trusted, and accessible, but Livermore scientists are constantly pushing to incorporate higher fidelity data to achieve even greater location accuracy and a lower detection threshold. An improved model called LLNL-Global 3D (G3D) extends velocity profiles from the crust and upper mantle used in RSTT to features in Earth’s lower mantle, all the way to the core–mantle boundary. LLNL-G3D retains the same basic node structure but does not incorporate the travel-time approximations that RSTT uses to achieve millisecond computational time. Instead, it calculates the best 3D travel-time solution for waves that propagate from the surface through the deepest parts of Earth.

Seismologist Nathan Simmons, who has led the development of LLNL-G3D, says, “RSTT is well suited for fast 3D travel-time estimates of waves that do not travel too deep into the upper mantle. Most of the time it’s a very good approximation. However, we wanted to build a more explicit representation of the whole Earth that takes into account really complicated and deep geologic structure.” The new model image, which he compares to a geologic computed

tomography (CT) scan, allows for 3D travel-time prediction for energy confined to the shallow mantle, as well as energy travelling deep into Earth. The enhanced geologic detail improves seismic epicenter accuracy to about 4 to 5 kilometers in well-sampled cases. This improvement in event epicenter accuracy

is significant for several regions, such as the Middle East, where RSTT cannot fully capture the effects of the complicated geologic structure.

Although LLNL-G3D is still in its basic research phase, Simmons anticipates it will see widespread use within a decade. One disadvantage of this more-accurate

model, however, is that it requires 100 to 1,000 times longer to compute a travel time than is required by ultrafast RSTT.

Physics Experiments Fill the Gap

Myers emphasizes that the historic collection of seismic data from underground nuclear explosions may

Studying the 2014 Napa Quake

Seismologist Artie Rodgers is using Livermore supercomputers to simulate the ground motion of the magnitude-6.0 earthquake that struck the southern Napa Valley in California on August 24, 2014, rupturing a 12-kilometer stretch of the West Napa Fault. One fatality, 100 injuries, and more than \$100 million in damage resulted from the quake, the largest to hit the San Francisco Bay Area since the magnitude-6.9 Loma Prieta event in October 1989.

The simulations by Rodgers and team are testing four different rupture models that attempt to describe how seismic waves were generated in the geologic strata underlying the greater Napa area. Two models are from the University of California (UC) at Berkeley, one from UC Santa Barbara, and one from the California Institute of Technology. Rodgers combines each model with a three-dimensional (3D) subsurface geologic model developed by the U.S. Geological Survey (USGS) in Menlo Park. “Broadly, all four models describe the same thing, but they differ in details because each is based on a different method and type of seismic data. We want to see whether one provides better predictions of the recorded motions.”

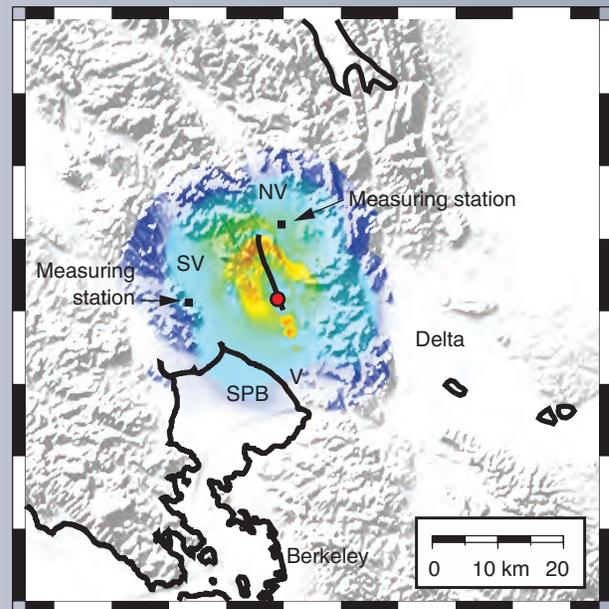
The Bay Area is home to hundreds of seismometers and Global Positioning System sensors, and so the quake generated a copious amount of high-quality data, which was available almost immediately to earthquake scientists and engineers. At the same time, current simulation capabilities far exceed what existed in 1989, allowing Rodgers’ team to perform higher resolution simulations than have generally been conducted. “We’re trying to improve our understanding of the shaking and damage that can accompany earthquakes. Advanced simulations can give stakeholders, policymakers, and the public a more accurate idea of what to expect from future quakes on this and other fault lines.”

The simulations are performed with the Seismic Wave 4th Order (SW4) code developed by Livermore computer scientists Anders Petersson and Bjorn Sjogreen. The simulations run on the Laboratory’s Cab supercomputer, a 430-teraflop Linux system, and take 6 hours to complete with 4,000 microprocessors running in parallel. “What used to be record-breaking calculations are now routine, but as we learn more we want to push these runs to higher resolution,” Rodgers says.

The simulations show the effectiveness of 3D models. Shaking can be seen to move slowly across the sedimentary structure of the Napa Valley, with seismic waves effectively trapped as they bounce

around in the valley. Such detail is missing from simpler simulations without detailed 3D structure.

Rodgers notes the Napa quake caused widespread damage, especially to unreinforced masonry buildings, but nowhere near the devastation that would be expected from a magnitude-7 quake along other faults in the Bay Area. Rodgers says that with strong ties to California universities and USGS, and with its 3D simulation expertise and some of the world’s most powerful high-performance computing resources, “Livermore is uniquely situated to help California understand shaking in the future and prepare for damaging quakes.”



This snapshot of the ground motion from the south Napa earthquake shows the magnitude of ground velocity (centimeters per second) scaled according to color. The event started at the epicenter (red circle) and ruptured along the fault (thick black line). Squares mark the locations of seismogram measurements. Place names are Napa Valley (NV), Sonoma Valley (SV), Vallejo (V), and San Pablo Bay (SPB).

not be representative of all future nuclear seismograms. In particular, future explosions may be conducted in different rock types and may not adhere to established relationships between explosion yield and emplacement depth. To fill the gap in experimental data, the NNSA laboratories launched the Source Physics Experiment, a series of underground chemical explosive tests. Conducted at the NNSA's Nevada National Security Site, these nonnuclear explosions are helping to fill the gap in experimental data to study the generation of seismic waves from explosions.

"We're looking at explosion yield and depth of device burial because the historical record provides little or no data on small and deep explosions," says Myers. The series of experiments is providing data in a controlled environment to test physics models. Heavily instrumented explosions are being conducted first in granite, a material that is strong and heavily fractured. The fractures appear to enhance the generation of S-waves, which can make an explosion look more like an earthquake. The

explosions in granite will be followed by explosions in alluvium, which is very weak and has fewer fractures.

The test results are being used to refine computational models of seismic wave generation using Livermore's GEODYN code. "We want to make sure our codes match not only the historic data set but also new data from these small explosions," comments Myers.

Tapping the Power of Big Data

The CTBT's global monitoring network, which is nearing completion, will consist of 50 primary and 120 auxiliary seismic stations, but thousands of other sensors worldwide are also recording or detecting seismic signals. "Seismic sensors are ubiquitous and are generating prodigious amounts of information that must be stored and should be processed," says Myers. Currently, Lawrence Livermore stores about 600 terabytes of seismic information, encompassing 5 billion seismic measurements.

"If we could make use of all this data, we could do some pretty incredible things," Myers states. The process of efficiently storing, sorting through, and

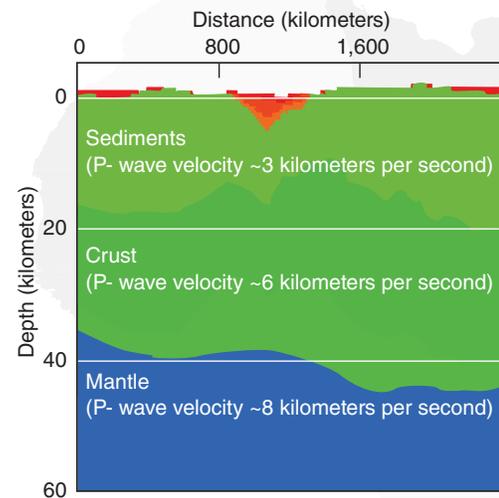
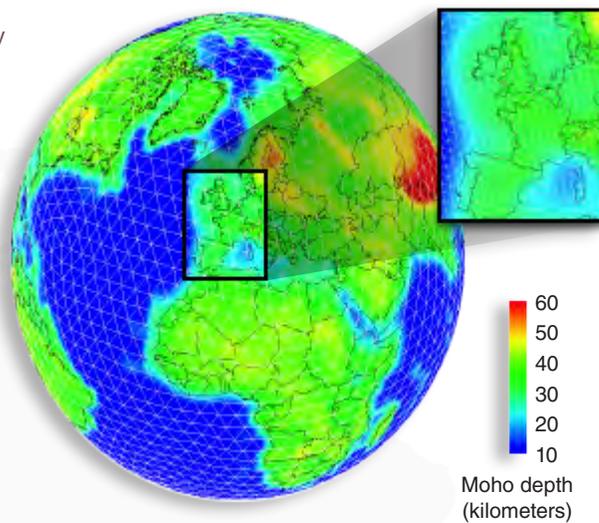
finding new meaning in enormous volumes of data is a key objective of big data (that is, data-intensive analysis), and Livermore scientists have been among the leaders of this relatively new field. They have already reduced the time it takes to cross-correlate Livermore's trove of seismic data from a month to a day. "With big-data techniques we can now test new ideas in a day," he notes.

One way to make use of big data would be to compare incoming seismic data associated with an underground explosion with the historic record of underground nuclear explosions and earthquakes over the past several decades. The result could lower monitoring thresholds and make possible 100-meter accuracy for locating underground tests at known test sites and 1-kilometer accuracy for other areas. "We're only in the infancy of using big data," Myers says, "but we see how it has the potential to transform the way we perform international monitoring."

Discoveries in Plate Tectonics

The tools that Livermore scientists have developed to generate ever

(left) The RSTT model accounts for crust and upper mantle seismic velocity variations by dividing the Earth's surface into about 41,000 nodes that form the vertices of triangular tiles. Node spacing is approximately 1 degree of arc (about 111 kilometers). Color indicates depth of the Moho discontinuity, the boundary between the crust and mantle. (right) A vertical profile of seismic velocity at each node is interpolated to render a three-dimensional model of Earth's crust and upper mantle.



more-accurate tomographic images of Earth's interior for nuclear explosion monitoring have had significant byproducts in other areas of science. For instance, increased resolution has recently revealed new, intriguing features that provide evidence for how tectonic plates move, collide, and are subducted into the lower mantle, improving our understanding of how Earth evolved. (Subduction is the process by which one tectonic plate slides under another plate and sinks into the mantle.)

One of the newly discovered features in the LLNL-G3D model is a tectonic plate located beneath the southern Indian Ocean, stretching southward from Indonesia to the submerged volcanic Kerguelen Plateau near Antarctica, and eastward beneath Tasmania. This plate, called the Southeast Indian Slab, resembles the ancient Farallon Plate that was discovered by seismologists in the late 1980s. The anomalously high seismic velocity exhibited by the plate indicates cooler features once at Earth's surface.

The Southeast Indian Slab is believed to have sunk mostly during the Jurassic period 150–200 million years ago, when the Indian and Australian subcontinents were close to one another in what is now the southern Indian Ocean. The plate had gone unnoticed until spotted by Simmons, who credits his discovery to advances in data-processing techniques, better data from numerous published reports, and more-advanced imaging methods. "We do a lot to the data we receive that enhances our ability to reveal new structures," says Simmons.

The research suggests that subducted plates can get stuck within the upper mantle a lot longer than previously expected, until they push through to the lower mantle. Simmons says there are intriguing links potentially connecting this ancient subduction episode

with volcanic processes in the Indian Ocean and the breakup of supercontinents that existed in the distant past.

Advancing Science—and Security

Livermore research works to better understand and predict signals from earthquakes. It is also enhancing scientific understanding of the complex structure of Earth, how it has evolved over hundreds of millions of years, and how it continues to evolve. But the most important application to national security is that by enabling the use of regional data in existing monitoring systems, new Livermore technology lowers monitoring thresholds and engages the international community as never before in the effort to ensure compliance

with the CTBT's nonproliferation regime. With technologies such as RSTT and LLNL-G3D, Livermore seismic research is improving the ability of the United States and her allies in nonproliferation to monitor nuclear explosions anywhere in the world.

—Arnie Heller

Key Words: Comprehensive Nuclear-Test-Ban Treaty (CTBT), data-intensive computation, E. O. Lawrence Award, earthquakes, LLNL-Global 3D (G3D) model, nonproliferation, nuclear testing, P-wave, Regional Seismic Travel Time (RSTT) model, S-wave, seismic modeling, Source Physics Experiment (SPE).

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To date, 66 nations (light green) have adopted RSTT in the international effort to monitor for seismic events, including underground nuclear explosions.

Supporting an Exercise of Global Importance

SOMEWHERE in a remote part of the world, the ground trembles with terrific force. The underground rumbling awakens a sensor network that measures the seismological, radionuclide, hydroacoustic, and infrasound qualities of the event. The sensor-captured information also triggers a globally coordinated investigation to confirm whether the source of the tremor is an illicit nuclear explosion.

In 1996, the United Nations opened for signature the Comprehensive Nuclear-Test-Ban Treaty (CTBT), which bans any kind of nuclear explosion anywhere on the planet, including nuclear test explosions. Until the treaty is ratified by all required states and comes into full force, the Preparatory Commission for the CTBT Organization (CTBTO) is provisionally operating the worldwide monitoring network. Based in Vienna, Austria, CTBTO is also developing an overall verification regime for when the treaty enters into effect.

When requested by a CTBT member state, a CTBT executive council will review the findings of monitoring activities (see feature article beginning p. 4) and determine whether further investigation is warranted for a suspected treaty violation. When the council deems that an investigation is justified, a team of 40 inspectors will be granted a small window of opportunity—only 140 days—to conduct a rigorous on-site inspection (OSI) in the area of interest. In this allotted time,

the team must search a 1,000-square-kilometer area to find the suspect site. Fortunately, the team has at its disposal a wide range of technologies to narrow down the geographic area and identify any relevant materials. Some of these systems can capture or detect the radioactive materials and gases that provide the best evidence of whether a nuclear explosion has indeed occurred.

With support from the National Nuclear Security Administration's (NNSA's) Office of Nuclear Verification, Livermore scientists and engineers took part in CTBTO's Integrated Field Exercise 2014 (IFE14). An event of unprecedented scale—involving more than 200 participants—IFE14 was hosted in Jordan and simulated nearly all the steps of an OSI, from the initial request for inspection to the return of all equipment and personnel to their home bases. Several years in the making, the exercise tested the current state of OSI capabilities and demonstrated how seamlessly a set of techniques could be integrated into a comprehensive system to detect the signatures of an underground nuclear explosion. Livermore technologies that identify radioactive isotopes and collect subsurface noble gas emissions featured prominently in the exercise, and Laboratory scientists participated as subject-matter experts and role players. The five-week exercise provided insight into the execution of an OSI and the functionality of the technological assets to deploy during an actual inspection.

Pinpointing a Radioactive Source

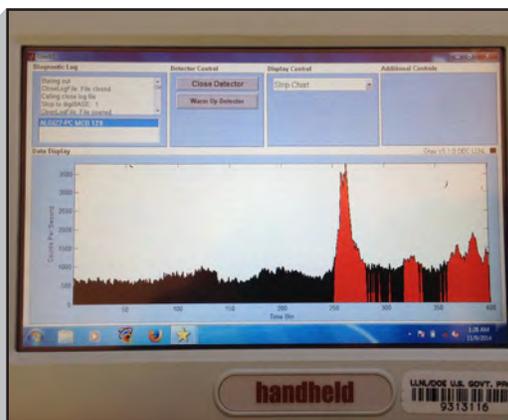
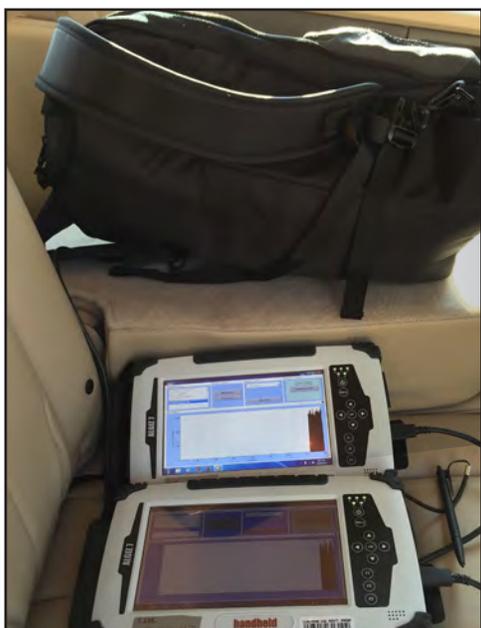
To be suitable for an OSI, a technology must be reliable, robust, mobile, and operable by inspectors who, although cross trained in many techniques, may not be experts in that specific technology. It must also effectively separate background radiation emitted by benign sources, such as medical isotopes used in hospitals or those that occur naturally in the environment, from radiation related to a nuclear explosion. “Our goal is to detect and characterize relevant radiation sources that could trigger an international assessment of whether there has been a treaty violation,” explains Steven Kreek, a Livermore radiochemist and leader of the Nuclear Detection and Countermeasures Research and Development Program in the Laboratory’s Global Security Principal Directorate. “No one technology can do it all,” adds Kreek. “It’s about using an array of techniques to first reduce the search area and then make specific, localized measurements to pinpoint a possible detonation site.”

Lawrence Livermore’s portable radiation detectors were used in the setup stage of the exercise. These sodium-iodide-based gamma-ray detection devices were either carried in a backpack to survey rough terrain or deployed by automobile to search for anomalies indicating a possible hot spot. The devices were used in the OSI exercise to quickly detect buried radiation sources and to experimentally validate the anticipated performance of other similar technologies used by the inspection team. Kreek, who served on the IFE14 control team, explains, “Our tests with these detectors during the setup phase of the exercise helped to validate whether the CTBTO inspection team could observe what the

control team wanted them to observe.” The detectors were based on Livermore’s Adaptable Radiation Area Monitor, winner of a 2005 R&D 100 Award. (See *S&TR*, October 2005, pp. 6–7.) The highly efficient, easily transportable device, also a sodium-iodide-based system, was initially developed for first responders, who typically have limited expertise in operating radiation detectors.

Sodium-iodide-based devices have low energy resolution, which limits their use to finding and localizing radiation anomalies rather than characterizing the radiation sources in great detail. During the OSI, higher energy-resolving germanium-based instruments were used to detect, identify, and quantify surface-deposited radionuclides and characterize specific sites. Previously, the application of solid-state germanium-based gamma-ray detectors was hindered by their need for cryogenic cooling, usually with hazardous, difficult-to-transport liquid nitrogen. A decade ago, however, Livermore scientists made these instruments more field deployable with a portable, battery-powered, integrated electromechanical cooling system.

Livermore’s electromechanical cooling system has also been incorporated into several other Laboratory-developed and now commercially available gamma-ray detectors, some of which were featured at IFE14. For example, ORTEC’s Detective, a portable gamma-ray detector, was used to quickly and accurately survey areas of hundreds of square meters and identify sources of interest. “It is important to note,” says Kreek, “that many of these gamma-ray detectors were loaned to CTBTO by different countries for the exercise. Such widespread adoption illustrates the far-reaching



During the Integrated Field Exercise 2014 (IFE14) of the Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO), car- and backpack-transportable radiation detectors developed at Livermore were used to validate the performance of similar technologies used by the inspection team. The detectors are based on Livermore’s Adaptable Radiation Area Monitor, winner of a 2005 R&D 100 Award.

impact Livermore’s detection technology and its electromechanical cooling approach have had in making high-resolution gamma-ray spectroscopy field portable.” ORTEC has broadly adopted the cooling technology for its high-purity germanium detectors, including the model loaned by Idaho National Laboratory for IFE14.

The “Smoking Gun”

Detecting significant levels of radioactive noble gases in the soil provides the highest level of certainty that an underground nuclear explosion has recently occurred. In fact, specific isotopes of xenon and argon are considered the “smoking gun” for a nuclear explosion. Livermore geophysicist Charles Carrigan explains, “We can extract these gases from the subsurface to get a better idea of what has happened underground.” In 1996, Carrigan was the lead author of a seminal scientific paper that demonstrated for the first time how the presence of noble gases, specifically isotopes of xenon and argon, could be used as fingerprints of a nuclear explosion. (See *S&TR*, January/February 1997, pp. 25–26.) The soil-gas-sampling techniques used for that work have since provided the basis for some OSI protocols and have resulted in the development of Livermore’s Smart Sampler, which autonomously captures subsurface gas from locations suspected of containing enhanced levels of noble gases. (The Smart Samplers used in IFE14 were provided by NNSA’s Office of Proliferation Detection.)

The Smart Sampler collects samples by either extracting gases directly from a sampling tube inserted to a shallow depth—3 to 10 meters—in the subsurface or from a coil of perforated tubing laid out on the ground and covered by a tarp or plastic sheet to prevent atmospheric infiltration. A single Smart Sampler can draw gases from five such sampling locations simultaneously.



In IFE14, the ORTEC Detective, a germanium-based detector featuring Livermore’s electromechanical cooling system and easy-to-use analysis interface, helped inspectors survey vast areas and identify sources of interest.

The Laboratory’s Charles Carrigan (left), portraying a representative of the inspected state during IFE14, evaluates background radon levels in a storage bag containing subsurface gases captured by the Livermore-developed Smart Sampler.



Computer-controlled flow meters and valves route the gases for sample collection and transport back to a laboratory for analysis.

Tracer gas studies had previously demonstrated that atmospheric pressure fluctuations strongly influence concentrations of surface-collected gases from an underground explosion. Carrigan and other Laboratory scientists, however, were the first to show that the efficiency of collecting noble gases might also be dramatically improved by triggering collection to rising subsurface radon concentrations. Radon is a noble gas produced by the decay of naturally occurring underground uranium. Says Carrigan, “We can potentially use radon as a natural tracer gas, observed in real time by the Smart Sampler, as an indicator of higher concentrations of the far more difficult-to-measure argon and xenon gases we really care about.” Existing at higher concentrations below the surface, radon is also a good indicator of whether the sampling tube is collecting gases only from the subsurface or also from infiltration from the atmosphere, which would be indicated by a precipitous drop in measured radon levels.

When aboveground barometric pressure drops below subsurface pressure, the resulting pressure gradient allows subsurface gases to flow out more freely. “Bad weather, including snow and thunder storms, are often associated with such barometric pressure drops,” says Carrigan. “The resulting conditions on the ground can pose serious health and safety risks to anyone manually operating the equipment at the time when gas collection is best.” The Smart Sampler solves this problem with its capability to automatically begin sampling according to atmospheric pressure or radon levels. “When the system senses a fall in barometric pressure or an increase in radon level, it begins sampling and can take several two-cubic-meter gas samples a day,” states Carrigan. Another advantage of this device over manual sampling systems is that it can monitor its own power supply and lower power consumption to prevent damage to the batteries until recharging. The Smart Sampler even has sensors to detect when tampering occurs—an important feature in a potentially hostile environment.

During IFE14, the Smart Sampler collected gas samples from several sites for analysis at the inspection team’s base of operations. “Although I was involved in the scenario in the role of the inspected-state party, I was also available to help make sure the systems were running properly,” says Carrigan. “At one point, the inspection team thought the equipment was being tampered with by the inspected-state party, and I was able to show that the systems were simply operating as deployed by the inspectors.” As the scenario played out, one of the sites provided subsurface noble gas samples consistent with a simulated underground nuclear explosion. Should the need arise in the future, the Smart Sampler can thus be a valuable tool for providing nearly irrefutable proof of a treaty violation.

Ready and Waiting

IFE14 provided an opportunity for CTBTO and its technical support teams to further develop and evaluate their on-site



At the end of IFE14, members of the CTBTO inspection team (left, blue shirts) meet with members of the inspected-state party (red shirts) to deliver the preliminary findings.

verification process and to test the capabilities for when the treaty enters into force. For Livermore and other organizations that develop detection technologies deployable by CTBTO, the exercise also demonstrated how their technologies could work in concert to collect evidence of a nuclear explosion. The results were highly encouraging.

Nuclear security is a paramount responsibility and an ever-increasing challenge faced by the global community. Lawrence Livermore has a long history of studying nuclear debris and developing radiation detection technologies and other diagnostics, stemming from decades of research and experience with nuclear weapons design and explosive testing. Today, Livermore’s expertise in this area is leading to innovative technologies that are improving our detection capabilities for present and future applications, including a reliable inspection toolkit for the global community’s nuclear nonproliferation efforts.

—Caryn Meissner

Key Words: Adaptable Radiation Area Monitor, Comprehensive Nuclear-Test-Ban Treaty (CTBT), Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO), gamma-ray spectroscopy, Integrated Field Exercise 2014 (IFE14), noble gas, on-site inspection (OSI), radiation detection, Smart Sampler.

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Just Passing Through Bridging the Communications Gap between Cells and Circuits

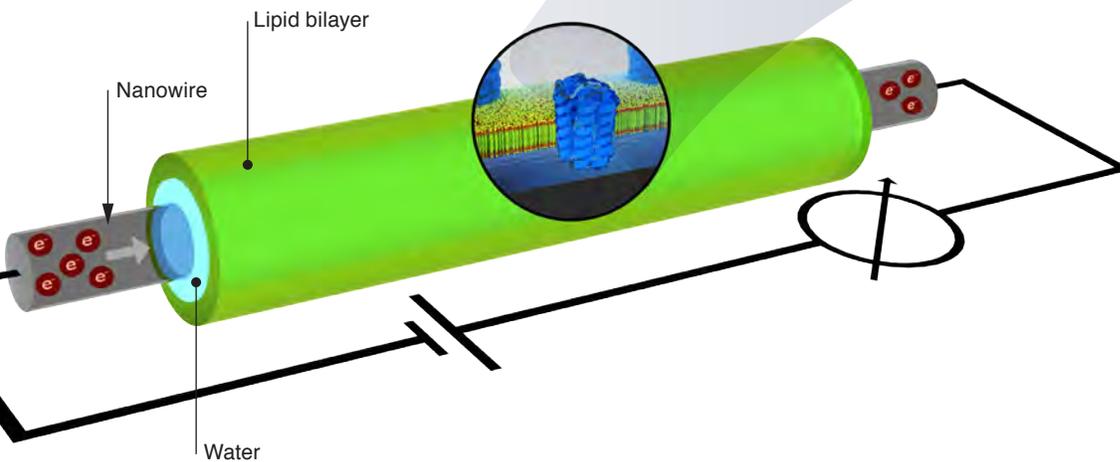
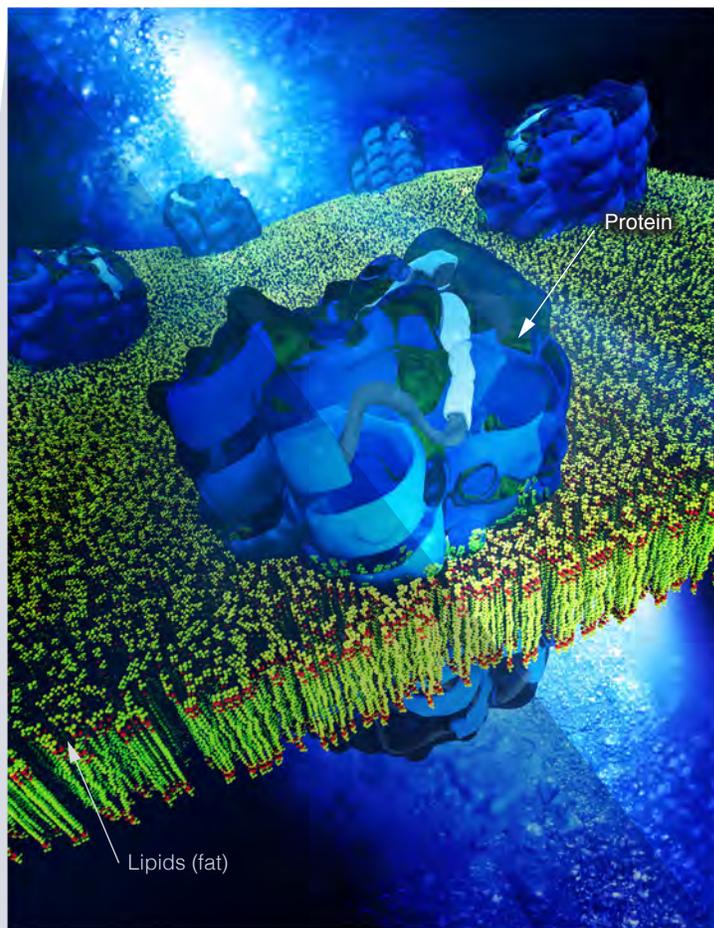
NATURE and scientists have both come up with clever and efficient ways to move information around in their respective systems. Whereas living cells use ion fluxes moving across cell membranes to transmit instructions and other information, electronic devices, such as computers, use electrons moving through wires. Both signal-passing methods depend on charged particles: Ions are either positively or negatively charged, while electrons carry a negative charge. Livermore scientist Alex Noy leads a team of researchers exploring innovative ways to connect the two “charged” worlds of living biology and electronic circuits by developing synthetic analogs of the ion channels found in biological membranes. Such a communications bridge could open new possibilities in synthetic cells, targeted drug delivery, and biosensing. Beyond that, this research could also lead to devices that are reflexive—responding as do nerves, muscles, and brains—using circuits that speak the signaling language of our cells.

Translating Ions to Electrons

Biological cells communicate in many ways, but in most cases it comes down to controlling the flow of ions such as calcium and potassium from outside to inside the cell or vice versa. Because the environment inside a cell must be well controlled even when conditions outside the cell are fluctuating, a cell has a gatekeeper, the cell membrane. Embedded in the cell membrane is a system of pores, pumps, and shuttles that actively or passively transports specific ions and molecules through this natural barrier. (See the box on p. 18.)

Noy and his team, including Livermore’s Ramya Tunuguntla, Jia Geng, Huanan Zhang, and Kyunghoon Kim, are focusing on the electrical aspect of transmembrane communications. “What we want to do is tie the worlds of electronics and biology together,” explains Noy. By no means a trivial matter, bridging this gap required an innovation to “translate” the language of ions into that of electrons. The technique that Noy and his team chose for this daunting challenge is a system based on a lipid-coated nanowire. A silicon wire measuring only 80 nanometers in diameter is surrounded by a thin film of water or other fluid, over which a lipid bilayer is deposited, creating a tubular shielding made out of the same material as a cell membrane. “Lipid bilayers are virtually impermeable to ions and large molecules and have limited permeability for water and small, uncharged molecules. Thus, they form a highly efficient nanoscale barrier system,” Noy explains. The lipid-coated device is then placed in solution, and the current flowing through the wire is measured with electrodes attached to both ends. (See *S&TR*, April/May 2010, pp. 18–19.)

This lipid-coated nanowire provides a versatile platform to which Noy and his team attach smaller structures. Just as one pokes a plastic straw into a juice box, Noy’s team can insert hollow structures—designed to transport specific types of ions—from the exterior, through the lipid membrane, and into the fluid-coated nanowire “cell.” The structures allow ions to pass from the interior into the surrounding solution, changing the interior fluid’s pH. This pH change then alters the conductance of the nanowire’s surface, varying the current flowing through the wire—a change detected by the electrodes. In short, the lipid-coated nanowire functions as a sensing device that the team can use to translate ionic signals into electronic ones. Thus the team has begun “cracking the code” of living cells.



To join the worlds of biology and electronics, a team at Lawrence Livermore developed a sensing device that mimics (top) a cell and its membrane—in which proteins act as a conduit through the membrane’s lipids—“translating” the ion fluxes of the biological world into the language of electrons spoken by electronic devices. (left) A silicon nanowire (gray) surrounded by a film of water (blue) is coated with a lipid bilayer (green). Ions entering through an ion channel change the pH of the water, inducing a change in the wire’s current. This current change is a signal that can be detected and translated into useful information. (Rendering at left by Ryan Chen.)

Channeling Drugs and DNA

With the sensing device in place, the team's next step was to create synthetic analogs to the protein channels that regulate the flow of molecules through the cell membrane. Noy explains, "These protein channels are quite amazing. They operate with high efficiency and exquisite selectivity. In membranes, they form pores that open and close, work as pumps, and even act as voltage-gated ion channels."

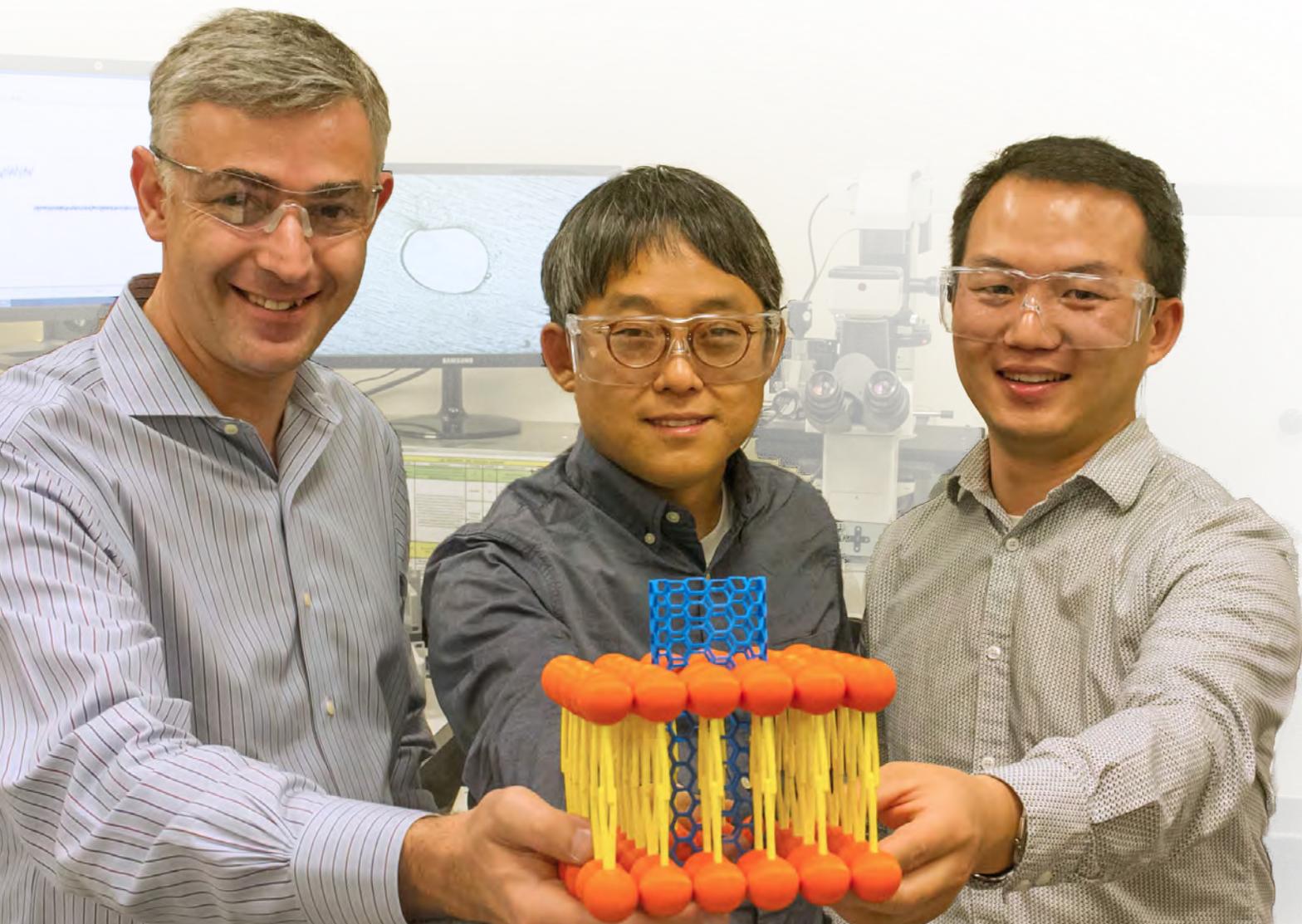
The same basic approach as the nanowire sensing device was also used in designing a new way to transport large molecules into a cell. In ongoing projects funded by Livermore's Laboratory Directed Research and Development Program and DOE's Office of Basic Energy Sciences, Noy and his team are developing and testing artificial, inorganic ion channels comprising nanometer-scale tubes of carbon—carbon nanotubes. Their collaborators include

Livermore scientists (from left to right) Alex Noy, Kyunghoon Kim, and Jia Geng hold up a model of a carbon nanotube that can be inserted into live cells, an achievement with potentially revolutionary applications in medicine and other fields. (Photograph by Julie Russell.)

Moving Molecules: Passive or Active

Nature employs several basic types of membrane transport, depending on the substance being transported and the direction the substance is moving—toward an area of lower or higher concentration of the substance. The most common transport method is passive diffusion, in which molecules move through a membrane from areas of high concentration to low concentration, or "down the concentration gradient." Oxygen, carbon dioxide, and most lipids enter and leave cells by such simple diffusion, with pores and channels through the membrane often providing the avenue of travel.

Ways also exist for a substance to move across a membrane from low concentration to high. Such situations involve active transport, or pumping, in which the cell provides energy in some fashion to pump the substance so that it moves against the concentration gradient. One example is the "sodium pump," which pumps sodium ions out of cells while transporting potassium in, maintaining the necessary gradients of each ion in the body's tissues.



researchers from the Molecular Foundry at Lawrence Berkeley National Laboratory, the University of California's Merced and Berkeley campuses, and Spain's University of Basque Country.

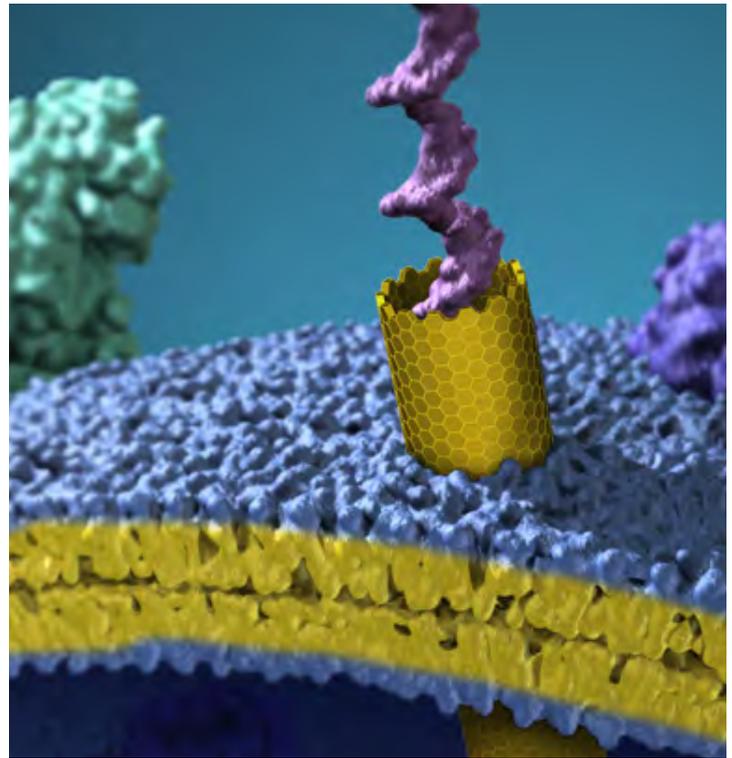
The inner channel of a carbon nanotube is narrow (approximately 1.5 nanometers across), hydrophobic, and very smooth—all properties that mirror those of biological pores. “We start with commercially produced carbon nanotubes that are tens of micrometers in length and use a special technique based on sound-wave energy to cut them into pieces about 5 to 15 nanometers in length, which is close to the thickness of the lipid membrane,” says Noy. Earlier experiments and simulations indicated that a carbon nanotube of such a length would self-insert into the membrane to form what is essentially an artificial pore. “Our focus was to see if these carbon nanotubes, or nanotube porins, as we call them, could be used for membrane transport,” adds Noy. The team showed that nanotube porins did indeed spontaneously self-insert into the lipid bilayer, at an angle perpendicular to the membrane plane, and did the job they were intended to do—transporting ions successfully in and out, just like actual protein-based cell pores do.

The researchers measured transport rates of individual porins as well as porin ensembles. They placed porin-pierced liposomes (small spheres of lipid bilayers) in a high-salt solution. “The concentration gradient creates a driving force for diffusion,” explains Noy. In single-pore experiments, the porin transported single-stranded DNA at a speed compatible with nanopore sequencing. In this type of sequencing, a narrow nanotube forces a coiled nucleic acid to unravel, transporting the nucleotides in single file. Each nucleotide changes the ion flow and affects the current differently, generating a signal that reveals the DNA sequence. If achievable with porins, this revolutionary new sequencing technique would require minimal sample preparation and be less expensive and faster than other techniques, making it possible to sequence bigger genomes in a practical length of time. (See figure at right.)

In addition, the team demonstrated that these synthetic pores can also spontaneously insert into the membranes of live mammalian cells and perform the same functions as protein pores. Using the patch-clamp technique, which records the currents of single or multiple ion channels in cells, they found that porins that self-inserted into the membranes of living cells have the same conductance dynamics as laboratory-produced lipid-bilayer membranes. This work suggests the potential to reproduce biological functionality in a synthetic platform that would be integrated with living cells, such as replacing damaged natural pore channels with man-made “spare parts.”

A Wired Future for Bio

Looking to the future, Noy sees many possible applications for this seamless meld of living cells and electronic systems. Short of the science-fiction possibilities of a direct brain-to-computer connection, possible applications in biosensors and medicine include delivering drugs to specific tissues and treating the many



In this artist's view, a carbon nanotube has been inserted through the plasma membrane of a cell, forming a strawlike tunnel through which molecules can pass into the cell. The image shows a single long strand of DNA passing through that tunnel, illustrating one of many possible ways of using these artificial “pores” to deliver drugs or other molecules into targeted cells. (Image courtesy of Xavier Studios.)

human diseases that involve ion-channel defects, such as epilepsy, cardiac arrhythmia, and cystic fibrosis. In addition to DNA sequencing, carbon nanotube porins could also further research in nanosensors and synthetic cellular interfaces. A “kit” of pores could be assembled in different ways in Lego-like fashion, to form custom biological circuits. “We have a system and device that are biocompatible, robust, and small,” says Noy.

For the near future, the team plans to explore the integration of carbon nanotube porins with biological organisms. Beyond that, the sky is the limit for these tiny devices that enable cells and circuits to speak the same language.

—Ann Parker

Key words: cell membrane, porin, pore, carbon nanotube (CNT), biosensor, biosensing, ion-channel disease, lipid-coated nanowire, plasma membrane, synthetic cell, ion flux, liposome.

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Light yet Strong

MECHANICAL properties such as strength and stiffness depend on the base material of which a structure is made—how the material itself is structurally organized at the micro- or nanoscale and how dense it is, that is, the ratio of solid to empty space. As density decreases, so does strength, sometimes dramatically so. For most solids, halving the density will reduce strength to one-quarter (quadratic scaling) or one-eighth (cubic scaling) of its previous value. However, by engineering how a material is structurally organized, researchers can improve the scaling of strength to density. To give a macroscale example, a bridge built with lattice or truss supports will be both stronger and stiffer for a given weight than a basic beam bridge because the trusses increase the structure's rigidity and distribute the bridge's load over a much larger area, enabling the bridge to stretch or compress rather than bend and potentially buckle under loading. Similarly, I-beams, staples of modern construction, achieve a strength-to-weight ratio superior to that of solid beams by apportioning mass to the very top and bottom of a beam, where strains and stresses are greatest.

Livermore researchers are innovating techniques to create lightweight yet strong materials with features engineered at the micro- or even nanoscale. These scientists and engineers have taken a cue from architects and structural engineers, despite working at vastly different scales. “The inspiration for our work is architectural constructions made of metal trusslike structures that are designed to be lightweight and yet sustain a lot of weight,”

Mechanical engineer Julie Jackson examines an engineered test structure that is smaller than a match head but contains hundreds of tiny, repeating octet truss elements. Using these trusses as building blocks, Livermore and Massachusetts Institute of Technology researchers have created low-density materials that are remarkably strong and stiff. (Photograph by George A. Kitrinou.)



notes engineer Xiaoyu “Rayne” Zheng. “It’s civil engineering at the micro- and nanoscale.” Zheng is developing engineered, additively manufactured structures with hierarchical, architectural microscale features, while materials scientist Monika Biener is creating randomly structured, self-assembled materials with nanoscale features. Both approaches offer avenues to explore the relationship between mechanical properties, structure, and density at several scales and to even create materials with previously unattainable combinations of properties.

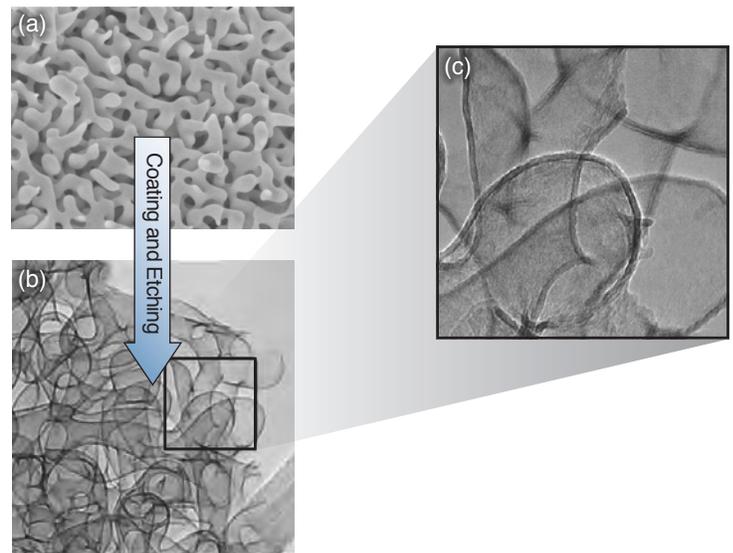
A Template for Success

Using the design element of interconnected, hollow, nanometer-scale tubes, Biener and her colleagues have produced porous structures with the lightness and high surface area of aerogels, a type of extremely low-density foam, but 10 times stronger and stiffer. In fact, these materials achieve quadratic scaling of stiffness with density, thought to be the best achievable for structures, such as foams, that bend under stress. “Ligament connectivity gives the foam a favorable strength-to-density ratio,” explains Biener.

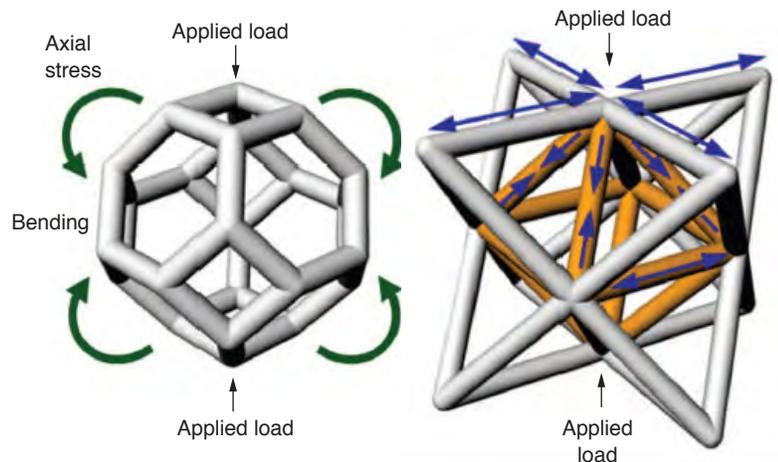
Synthesis of these materials begins with a gold–silver alloy structure. The scientists apply an acid to remove the silver, leaving behind a fine network of gold ligaments. Notes Biener, “Nanoporous gold is built by a self-organization process, which gives it a very unique spongelike structure and special features, such as a narrow pore size distribution. It also coarsens when exposed to heat, which gives us a way to tune the material.” Depending on the temperature to which the gold is heated, the team can adjust the pore size between 30 nanometers and 4 micrometers while preserving its characteristic shape.

Even the gold itself serves as a template for other materials. These have so far included aluminum, titanium, and zinc oxide, but the flexible synthesis process will eventually be extended to other metal oxides and maybe even other kinds of templates. To coat the gold’s surface with thin, uniform layers, the researchers use atomic layer deposition (ALD), a gas-based technique that enables atomic-level control of film thickness. Once coated, the material is shielded from further heat-induced pore size growth. ALD also enables some customization of density: The more layers applied, the denser the final material will be.

The gold is etched away, leaving a metal-oxide foam that has inherited the gold’s structure. The strong and stiff foam features two separate but interwoven networks of tubular pores—one where the gold originally existed and the other formed by the silver’s removal. Biener’s team can create foams up to several millimeters in diameter and with tube walls as thin as two nanometers.



These electron microscopy images show how a stiff, lightweight titanium oxide foam is created. (a) A spongelike nanoporous gold structure is the starting point. (b) The structure is coated with titanium oxide, and the gold is etched away to reveal a transparent, highly uniform material with excellent mechanical properties. (c) The foam’s hollow tubes are only 2 nanometers thick.



(left) Low-density materials with a random structure will typically bend, buckle, and eventually break when a load is applied. (right) However, low-density materials with an engineered architecture will stretch or compress rather than bend, thus achieving greater strength for a given weight.

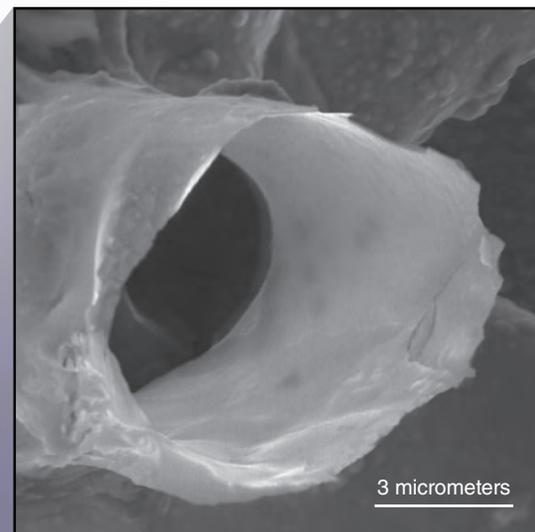
Laboratory researchers have begun to explore potential applications for these nanotubular metal-oxide foams. For example, their combination of ultralow density and high stiffness makes them ideal candidates for x-ray backlighters, which produce x rays to investigate the physical phenomena that occur in the extreme environment of a target bombarded with laser energy. During tests at the Omega Laser Facility in Rochester, New York, nanotubular titanium-oxide foams have yielded up to 17 times more x rays than standard titanium-doped silica aerogels. Biener and her colleagues are also investigating how the foams' high surface area and customizable structure, composition, and density could benefit other applications that currently use aerogels, such as filtration, catalysis, and energy storage.

Employing their own design tools and an additive manufacturing technology called projection microstereolithography, along with postprocessing techniques, Livermore engineers have created objects made of hierarchical, architected materials. This object is an octet fractal unit cell made of nickel and having hierarchical features across more than four orders of magnitude in length scale. (Images courtesy of John Vericella and Xiaoyu "Rayne" Zheng.)

Fractals Lend Their Support

A joint team of researchers assembled from the Laboratory and the Massachusetts Institute of Technology (MIT) and led by Zheng, Livermore additive manufacturing expert Chris Spadaccini, and MIT's Nicholas Fang has developed a micro-architected material with the same weight and density as aerogels but 10,000 times the stiffness. "These lightweight materials can withstand a load of at least 160,000 times their own weight," says Zheng. "The key to this ultrahigh stiffness is that all the microstructural elements in this material are designed not to bend under applied load." The team has demonstrated both linear and quadratic scaling of strength to density, depending on the lattice geometry they select. Linear scaling—a slower loss of stiffness as mass is reduced than with quadratic or cubic scaling—is not achievable with randomly organized structures such as aerogels.

Octet trusses serve as the basic building block for the stiffest and strongest structures. "We used the octet truss for our designs because it has an optimized geometry that is stretch dominated and relatively isotropic, which means that forces applied in different directions produce a similar response," Zheng explains.



A honeycomb structure, by contrast, is much stronger and stiffer in some loading directions than in others.

The lattice structures are created with projection microstereolithography, an additive manufacturing technique that uses ultraviolet light to imprint, layer by layer, a photosensitive polymer resin with a complex three-dimensional (3D) image. (See *S&TR*, March 2012, pp. 14–20.) A 3D model of the object is broken up into two-dimensional slices, which are projected onto a digital photomask. An ultraviolet light-emitting diode illuminates the miniature display, which reflects the image slice through a series of optics and onto the liquid resin, which hardens in the image's shape. Next, the sample is coated with more resin, and the next slice of the model is projected and imprinted on the material. Once the full pattern has been applied, excess resin is removed, leaving behind the completed object.

The efficient process can create objects up to a few centimeters in diameter and with features between 10 to 500 micrometers in only a few hours or less, depending on the size of the object and the complexity of the features. Notes Fang, "Now we can print a stiff and resilient material using a desktop machine. This allows us to rapidly make many sample pieces and see how they behave mechanically."

Microstereolithography is only compatible with a few materials, so the team has developed several postprocessing techniques for creating metal and ceramic lattices. Solid ceramic lattices can be made by mixing nanoparticles into the resin and then using a heat treatment to remove the polymer from the finished structure. Ultralight ceramic or metallic lattices with hollow struts are produced by coating a polymer lattice using electroless plating or ALD and then melting or etching away the polymer core. Regardless of the material, the resulting structures exhibit ultrastiff properties across a broad range of densities. "Our microarchitected materials have properties that are governed by their geometric layout at the microscale, as opposed to their chemical composition," says Spadaccini.

The researchers' next goal is to discover the smallest possible feature size achievable with the largest possible span, using a new Livermore-developed lens for the microstereolithography system. The lens will enable fabrication of parts up to 15 centimeters in diameter, an unprecedented size for this technique. "We are also embedding multiple levels of hierarchies into a material," notes Zheng. "Instead of making the material out of a single hierarchy and length scale, we are developing processes to make polymer, metallic, ceramic, and composite materials with multiscale features architected at successive length scales, from centimeters down to tens of nanometers." For example, the team produced a hierarchical lattice material made of nickel and having more than four levels of hierarchy, with features as small as tens of

nanometers. These fractal designs are allowing the researchers to build lighter, stronger, and larger objects than ever before, with exponentially larger surface areas. Ultimately, the team hopes to see their lattices adopted by transportation, electronics, aerospace, and other industries interested in ultralight products with maximum fuel efficiency and functionality, without sacrificing strength.

A Tailored Solution

While superior strength and stiffness are often desirable properties, sometimes other property pairings are called for, such as strength and compliance, that is, deforming slightly in response to, say, a workpiece being held in place. Mechanical engineer Howard Rathbun and his colleagues in the Defense Technologies Engineering Division were using another AM technique, selective laser melting (SLM), to build a series of heavy, high-density steel parts when they realized that their supporting jig was too stiff. The rapid cooling undergone by SLM parts during fabrication produces residual stresses, which were causing parts to distort and sometimes even break. Using SLM, they built a jig composed of macroscale bend-dominated lattice structures that was strong enough to support a part but had fewer and more compliant connections to accommodate distortions and prevent part damage. "In this situation, we were able to gain control by 'letting go,'" explains Rathbun.

The key, as Laboratory researchers have found, is designing the right material for the right application. "We're not limited to one design," adds Zheng. "We can create different architectures with diverse property combinations. We offer properties tunable by design, including energy absorption, ductility, conductivity, and strength." Work by Zheng, Biener, Rathbun, and others is introducing greater flexibility into the material design and synthesis processes by aiding researchers in understanding how to decouple properties that usually go together, such as strength and density, and bring together properties that are usually exclusive, such as temperature resistance and ductility. These efforts, supported by Livermore's robust design, manufacturing, and mechanical testing capabilities, will help scientists and engineers to tailor materials more precisely to a wide range of scientific and technological applications.

—Rose Hansen

Key Words: additive manufacturing (AM), aerogel, atomic layer deposition (ALD), backlighter, density, hierarchical material, isotropic, nanoparticle, nanoporous gold, nanotubular, octet truss, projection microstereolithography, selective laser melting (SLM).

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Patents

Synthetic Catalysts that Separate CO₂ from the Atmosphere and Gas Mixtures

Felice C. Lightstone, Sergio E. Wong, Edmond Y. Lau, Joe H. Satcher, Jr., Roger D. Aines
8,962,511 B2
February 24, 2015

Passive Chip-Based Droplet Sorting

Neil Reginald Beer, Abraham P. Lee, Andrew C. Hatch, Jeffrey S. Fisher
8,969,071 B2
March 3, 2015

Microwave Heating of Aqueous Samples on a Micro-Optical-Electro-Mechanical System

Neil Reginald Beer
8,969,767 B2
March 3, 2015

Radiological/Biological/Aerosol Removal System

Jeffery J. Haslam
8,979,968 B2
March 17, 2015

Inductrack III Configuration—A Maglev System for High Loads

Richard F. Post
8,985,030 B2
March 24, 2015

System and Method for Measuring Fluorescence of a Sample

Vincent J. Riot
8,988,684 B1
March 24, 2015

RF/Optical Shared Aperture for High Availability Wideband Communication RF/FSO Links

Anthony J. Ruggiero, Hsueh-yuan Pao, Paul Sargis
8,989,584 B2
March 24, 2015

Graphene Aerogels

Peter J. Pauzauskie, Marcus A. Worsley, Theodore F. Baumann, Joe H. Satcher, Jr., Juergen Biener
8,993,113 B2
March 31, 2015

Awards

Patrice Turchi was installed as **president of The Minerals, Metals, and Materials Society (TMS)** for 2015. An active member of TMS for more than 25 years, he has served on the TMS board of directors as chair of the Electronic, Magnetic, and Photonic Materials Division (now the Functional Materials Division), chaired the Alloy Phases Committee and various administrative committees, been a member of several technical advisory groups, organized 15 TMS symposia, and served as vice president of the society in 2014. Turchi's research interests encompass computational materials science and condensed-matter physics, with an emphasis on alloy theory from first-principles electronic structure and the stability and physical properties of complex assemblies. TMS covers the entire range of materials and engineering and has nearly 13,000 members in 94 countries.

Jeffrey Drocco was selected as a **Biosecurity Fellow** under the **Emerging Leaders in Biosecurity Initiative**, which is operated by the **University of Pittsburgh Medical Center**. Drocco is one of 28 fellows—selected from nearly 100 applicants—participating

in the competitive program, which is designed to create and sustain a multidisciplinary and intergenerational biosecurity community made up of young professionals and current leaders. The program includes presentations and briefings at the White House, the Pentagon, and the United Kingdom's Defence Science and Technology Laboratory and Pirbright Institute.

Lawrence Livermore climate scientist **Ken Sperber** received the 2014 **Editors' Citation for Excellence in Refereeing** from the **American Geophysical Union's (AGU's) *Journal of Geophysical Research: Atmospheres***. The citation is chosen by AGU editors, who are asked to select outstanding reviewers of submitted papers from the previous year, across all AGU journals. Sperber's specialty is the variability of monsoons on seasonal through decadal timescales. He is a longtime member of the Program for Climate Model Diagnosis and Intercomparison and is currently working to understand the potential impact of climate change on monsoons using numerical simulations from the Coupled Model Intercomparison Project Phase 5.

Seismic Research Making Waves

Lawrence Livermore scientists have long been leaders in seismic research to support monitoring under international nuclear testing treaties. One of the Laboratory's most significant accomplishments is a revolutionary seismic monitoring technology called the Regional Seismic Travel Time (RSTT) model. RSTT improves the accuracy of locating seismic events by using a three-dimensional (3D) model of the Earth's crust and upper mantle and by incorporating the regional data needed to improve accuracy. In addition, a model called LLNL-Global 3D extends velocity profiles from the crust and upper mantle used in RSTT to Earth's lower mantle and even the mantle-core boundary. Livermore researchers are also conducting chemical explosives tests to refine models of seismic wave generation, using data-intensive computing to glean new insights from seismic data accumulated over six decades of nuclear monitoring, and conducting supercomputer simulations to better understand ground motions from earthquakes. This includes helping Californians prepare for major temblors expected to occur in the future.

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Science-Based Stockpile Stewardship



The National Nuclear Security Administration's Stockpile Stewardship Program marks 20 years of outstanding success.

Also in July/August

- *A new forensic technique based on genetic variation in proteins could aid in human identification when DNA profiling is infeasible.*
- *Livermore researchers are developing a highly aerodynamic vehicle that can radically reduce fuel consumption in the transport sector.*
- *Two decades of the Stockpile Stewardship Program have led to innovative, nondestructive ways to assess the components and materials performance of nuclear weapons in the nation's stockpile.*

COMING NEXT ISSUE

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